The Angular Signal Modulation Observed in Double-Wave-Vector Diffusion-Weighting Experiments at Short Mixing Time: A Phase Evolution Perspective

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Purpose

Recently, the interest in double-wave-vector experiments [1] where two diffusion-weighting periods are applied successively in a single experiment, has increased due to their ability to assess microscopic anisotropy [2] or compartment sizes in biological tissue [3]. In the latter case, which involves a vanishing mixing time between the two diffusion weightings, the signal differs between the parallel and antiparallel orientation of the two wave vectors yielding a three-fold increased signal decay for the parallel orientation. Because in conventional diffusion-weighted experiments the polarity of the diffusion gradients has no influence on the signal decay, this difference is often considered to be surprising and, although a theoretical framework has been presented [1], raises the question whether this effect can be depicted illustratively. In this work [4], the signal difference is explained for diffusion between parallel planes on the basis of the phase evolution of the spins during the experiment demonstrating the crucial influence of gradient polarities. A detailed analysis of the phase distribution in the sample for small wave vectors, reveals the factor 3 for the corresponding signal decays as expected from the theory [1].

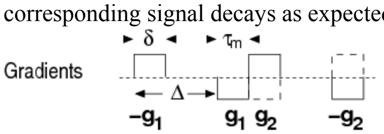

Figure 1: Basic pulse sequence for the double-wave-vector experiment with a mixing time of τ_m for antiparallel (solid) and parallel (dashed) wave vector orientations.

Outline of Content

The phase evolution during the experiment shown in Fig. 1 is sketched in Fig. 2. As in [1], short gradient pulse duration δ and a short mixing time τ_m between the two wave vectors as well as a long diffusion time Δ are assumed, i.e. diffusion-related displacements of the spins occur only during Δ.
The effect of the first wave vector is shown in the left column. Prior to the first gradient pulse all spins have the same phase (1st row) which changes when the first (dephasing) gradient pulse is applied (2nd row). After the long diffusion time, the spins of all positions have moved to anywhere in the pore which means that (i) the same phase distribution is found at any position and (ii) the distribution a mixture of all spin phases present prior to the diffusion time, i.e. a uniform distribution between –α and +α (3rd row). The second (rephasing) gradient causes a phase shift opposite to that of the first one yielding different centre phases at the different positions (4th row).
Regarding the second wave vector, the antiparallel orientation (centre column) will be considered first. Because the dephasing gradient of the second wave vector is the inverse of the preceding gradient and it is assumed that no time for diffusion is in-between, the last phase shift is reversed completely for all spins (2nd row). Thus, the phase distribution is the same for all positions (between –α and +α) and identical to the distribution after the diffusion time of the first wave vector. Consequently, it does not change during the second diffusion period (3rd row) and after the last (rephasing) gradient the phase evolution is identical to that after the first wave vector (4th row). This is obvious as for short δ and τ_m the two middle gradients cancel each other. Centre phases between –α and +α are obtained and a phase range of 2α at each position which upon averaging (5th row) yields phases between –2α and +2α, i.e. a total phase range of 4α. Thereby, phases larger or lower than 0 occur only in part of the volume.
For the parallel orientation (right column), the third gradient doubles the phase shift introduced by the second (2nd row) yielding centre phases between –2α and +2α while at each position a phase range of 2α is covered. During the second diffusion period, the spins mix up again yielding centre phases of 0 anywhere but a phase range of 6α (3rd row). Upon the last (rephasing) gradient, the centre phases are shifted by –α to +α at the different positions. Thus, the phases (5th row) cover a range between –4α and +4α, i.e. a total phase range of 8α. Thereby, phases between –2α and +2α are present all over the volume, i.e. not only the total range of the phases is increased compared to the antiparallel orientation but also the population distribution has broadened.
Analyzing the population of the individual phases in more detail yields a three-fold signal decay of the parallel orientation for small α.

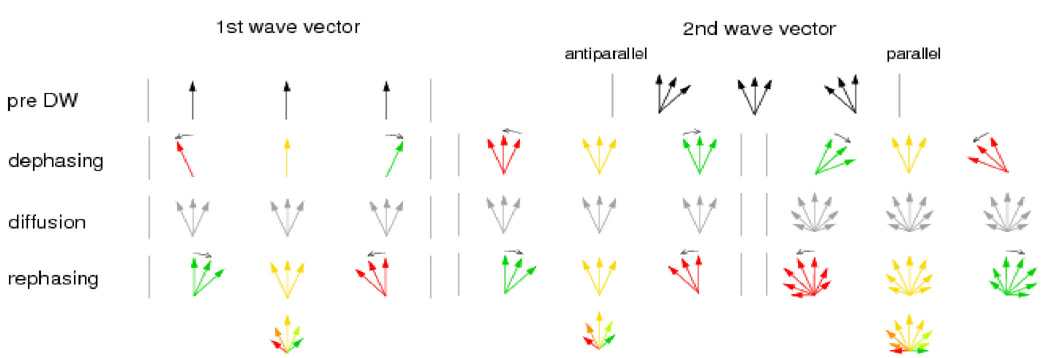

Figure 2: Schematic phase evolution in a double wave vector experiment with antiparallel and parallel wave vector orientations for spins between two parallel planes (vertical lines). For simplification only three spin ensembles, close to the planes and in the centre, are considered. Gradient pulses are applied in left-right direction and are assumed to introduce no phase effect in the centre and a phase shift of –α (red) and +α (green) close to the planes, respectively, depending on their polarity.

Summary

An illustrative depiction for the signal difference between parallel and antiparallel wave vector orientations in double wave vector experiments on restricted diffusion has been presented. For small phase shifts, it yields a three-fold increased signal decay for the parallel orientation as is expected from the theory [1].

References

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